

Neutrino Star as Galactic Cluster Dark Halo

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Abstract

Recent strong lensing data and rotation curves of dwarf galaxies indicate that many galactic clusters may have a soft core instead of a central cusp in their density distribution. This result challenges the standard CDM (Cold Dark Matter) theory prediction based on N-body simulations. We find that the observed density profile is consistent with that of a spherical gas of degenerate fermions such as neutrinos in hydrostatic equilibrium. Also, we compare two different models of the dark matter halo and their predictions for the hot gas profile.

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Recent strong lensing data and rotation curves of dwarf galaxies suggest that matter distribution takes the form of a soft core at the centers of some galaxy clusters [1,2]. However, N-body simulations based on the CDM theory predict that the density profile of the dark matter halo should be singular at the center which is called the NFW profile [3,4]. One possibility to resolve the discrepancy is that the dark matter may not be collisionless as assumed in previous simulations. They may interact with each other and form a profile different from the NFW profile. In the following, we show that indeed the observed density profile is consistent with that of a degenerate gas of massive neutrinos in hydrostatic equilibrium. We will first review a method of inferring the dark matter distribution from the density profile of the hot gas in a galaxy cluster [5,6]. Then we will demonstrate that one of the dark matter candidates, massive neutrinos, which can be either collisionless or self-interacting, can account for the observed profiles.

One of the most common methods to probe the dark matter distribution is to make use of the gas density profile. We assume that the hot gas is in hydrostatic equilibrium, i.e.,

$$\frac{dn_g(r)}{dr} = -\frac{GM(r)m_g n_g(r)}{kTr^2}, \quad (1)$$

where $n_g(r)$ is the number density of hot gas, $M(r)$ is the total mass enclosed within a radius r , k is the Boltzmann constant, and m_g is the mass of the gas particles. Here we assume that the hot gas is isothermal throughout the cluster, with a constant temperature T , which is valid as the heat conduction by electrons is quite efficient. By knowing the number density profile of the hot gas, we can probe the distribution of dark matter. There is a general form of the hot gas density profile called the β model [5],

$$n_g(r) = \frac{n_0}{[1 + \tilde{r}^2]^{3\beta/2}}, \quad (2)$$

where $\tilde{r} \equiv r/r_c$, r_c being the core radius, β is a parameter, and n_0 is the central number density. Different clusters have different values of n_0 , r_c and β . Now, we can solve Eq. (1) and Eq. (2) and get:

$$M(r) = \frac{3kT\beta r^3}{Gm_g(r^2 + r_c^2)}. \quad (3)$$

For r much greater than r_c , $M(r) \propto r$, whereas for r much smaller than r_c , $M(r) \propto r^3$, which means that the density is constant,

$$\rho \rightarrow \rho_c \equiv \frac{9kT\beta}{4\pi Gm_g r_c^2}, \quad r \ll r_c. \quad (4)$$

In general, from Eq. (3), we can obtain the mass density of the dark matter, assuming that the total mass is dominated by dark matter together with the hot gas,

$$\rho_{\text{DM}} = \frac{\rho_c}{3} \left[\frac{\tilde{r}^2 + 3}{(\tilde{r}^2 + 1)^2} \right] - m_g n_g(r), \quad (5)$$

which is quite different from the NFW profile,

$$\rho_{\text{DM}} = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}, \quad (6)$$

where ρ_0 and r_s are parameters. Possible sources of the discrepancy are problems in the NFW profile, or the β model, or the assumption of isothermal distribution in the cluster. For example, it has been proposed that including the cooling flow of hot gas in the above model will result in a dark matter distribution that is closed to the NFW prediction [7].

Nevertheless, the hot-gas method is model dependent and the uncertainties are still large. To understand more about the dark matter, one powerful and model independent alternative is to use strong lensing to probe the distribution of dark matter. This method still has large errors and is limited in data collection. One of the clusters studied recently is CL0024+1654 [1]. It was concluded that CL0024+1654 has a soft core in the center which is different from the NFW profile [8]. Furthermore, some observations of dwarf galaxies mass distribution also indicate that the inner halo density is nearly constant [2].

It has been proposed that cold dark matter may have weak self-interaction instead of being collisionless [9]. Following this suggestion, we assume that the dark matter can establish hydrostatic equilibrium,

$$\frac{dP_{\text{DM}}}{dr} = -\frac{GM(r)\rho_{\text{DM}}(r)}{r^2}, \quad (7)$$

where P_{DM} is the dark matter pressure. Then, we can combine Eq. (1) and Eq. (7) to get

$$\frac{dP_{\text{DM}}(\rho_{\text{DM}})}{\rho_{\text{DM}}} = \frac{kT}{m_g} \frac{dn_g}{n_g}. \quad (8)$$

From Eq. (8), we can obtain the equation of state (EOS) of dark matter $P_{\text{DM}}(\rho_{\text{DM}})$ from the hot gas density profile. If we assume a polytropic relation between the pressure and density of the dark matter,

$$P_{\text{DM}} = K \rho_{\text{DM}}^\gamma, \quad (9)$$

where K and γ are parameters in the EOS, Eq. (8) becomes

$$\ln \left(\frac{\rho_g}{\rho_{gc}} \right) = \frac{m_g \gamma K}{kT(\gamma - 1)} \left[\rho_{\text{DM}}^{\gamma-1} - \rho_{\text{DMc}}^{\gamma-1} \right], \quad (10)$$

with $\gamma > 1$, and ρ_{gc} and ρ_{DMc} are central density of hot gas and dark matter respectively. The hot gas density profile directly tracks the dark matter profile and is sensitive to the steepness of the dark matter EOS.

In the following, we consider massive neutrinos as a specific model of dark matter and solve the cluster core problem. At low density, neutrinos are collisionless as they have very small interaction cross-section. However, at high density they become degenerate, and they can therefore be in hydrostatic equilibrium. It has been proposed that such neutrino “stars” may be found in the centers of galaxies [10,11]. Here we propose that they may exist at the centers of galaxy clusters. Since the interaction cross-section of neutrinos is small, we can treat them as a zero temperature gas. The degenerate pressure for non-relativistic neutrinos is given by

$$P_\nu = \frac{h^2}{5m_\nu} \left(\frac{3}{8\pi} \right)^{2/3} n_\nu^{5/3}, \quad (11)$$

where n_ν and m_ν are the number density and mass of the neutrinos. We can then solve for the density profile of a neutrino star assuming hydrostatic equilibrium (shown in Fig. 1), which is expectedly similar to that of a white dwarf. Here we set the neutrino mass to be 3 eV and the central number density to be 10^8 cm^{-3} , which fits the observational data for clusters. The radius of the neutrino star is several kpc which is comparable to the cluster

scale. The total mass is about 10^{14} solar masses, which is also close to the total mass of a cluster. A neutrino star has a core in the center, the radius of which depends on the central mass density only. The higher the central mass density is, the smaller is the core radius and vice versa. The inner density profile is similar to the data obtained from gravitational lensing. This suggests that at least some clusters may be degenerate fermions dominated. From Fig. 1, we can approximate the neutrino star density profile as following: for $r \ll r_0$, $M(r) = Cr^3$, where C is a constant, and for $r \gg r_0$, $M(r) = M_0$, where M_0 and r_0 are the total mass and core radius of the neutrino star. Using the above approximation, we can analyse the density profile of the hot gas inside a cluster core if its mass is dominated by the neutrino star. If $M(r) = Cr^3$, we have

$$n_g = n_0 e^{-ar^2}, \quad (12)$$

where $a = GCm_g/2kT$. For $r \ll a^{-1/2}$, the hot gas profile is smooth and flat. Therefore, the core radius is

$$r_c = a^{-1/2} = \left(\frac{2kT}{GCm_g} \right)^{1/2}. \quad (13)$$

Clearly, r_c is not necessarily equal to r_0 , but it is affected by the central mass density of the neutrino star and temperature of the hot gas. In our model, for $T = 10^8$ K and central mass density $\rho_c = 10^{-25} \text{ gcm}^{-3}$, r_c is about 150 kpc.

We can also calculate the density profile of the hot gas numerically. In Fig. 2, we show the hot gas profile using the above parameters of a neutrino star, and we find that it is well fitted by using a β model with $\beta = 1.1$ and $r_c = 150$ kpc. This indeed agrees with the observational value of β between 0.9-1.1 [12,13].

We now compare the results of using three different models, the NFW dark matter profile, neutrino star model and hot gas self-bounded profile. Here, we continue to assume that the temperature of the hot gas is constant throughout the cluster. Fig. 3 shows the hot gas profiles from these three models. We can see that the three hot gas profiles have similar central mass density and temperature. However, the slopes of the hot gas profiles

for $r > r_c$ are different, being smallest for self-bounded model and largest for the neutrino star model. In fact, the slope of the hot gas profile depends not only on the dark matter profile but also on the temperature profile of the hot gas and velocity dispersion of the dark matter particles. Therefore, the dark matter profile obtained by using the hot gas profile alone is model dependent. For $r > r_0$, the total density profile is dominated by the hot gas and the total density tail ρ_T is approximately proportional to r^{-3} which agrees with the observational result [14]. To understand the dark matter distribution better, gravitational lensing is a potentially more powerful method. It is model independent, and we can know the mass density profile directly without using any hot gas model if the cluster is dominated by the dark matter. For example, the cluster CL0024+1654 observed by Tyson *et al.* does not have a cD galaxy, which means that the mass of dark matter is dominant at the center of the cluster [2]. Gravitational lensing data suggests that the NFW profile may not be correct.

We have shown in this article that observational data on cluster hot gas is consistent with the existence of neutrino stars, which can account for at least parts of the dark matter. But how are these neutrino stars formed? It is commonly believed that there is a cosmological neutrino background originating from the Big Bang [15], corresponding to a temperature of about 1 K now, or about 0.1 meV in energy scale. Therefore it is conceivable that cosmological neutrinos with rest mass even in the sub-eV range are non-relativistic. Recent experimental observations of neutrino oscillations point to a range of the mass difference between muon and tau neutrinos to be $5 \times 10^{-4} < \Delta m^2 < 6 \times 10^{-3} \text{ eV}^2$ [16]. Therefore at least one species of the cosmological background neutrinos should be non-relativistic, and the interplay between gravitational attraction and degenerate pressure makes it possible to create neutrino stars. We have carried out hydrodynamics simulations of their formation process, and preliminary results indicate that hydrostatic neutrino stars can indeed form with a wide range of parameters [17].

One of the interesting properties of the neutrino star is that it has a flat core, which agrees with the gravitational lensing data as well as the rotation curves of dwarf galaxies,

but contradicts with the NFW profile. Recently, Sand *et al.* has provided an upper limit of the slope of the central density profile $\alpha < 0.57$ which is different from NFW's ($\alpha = 1$) [18]. In our model, α is approximately zero. In order to solve the "core problem" of galactic clusters, more data will clearly be needed.

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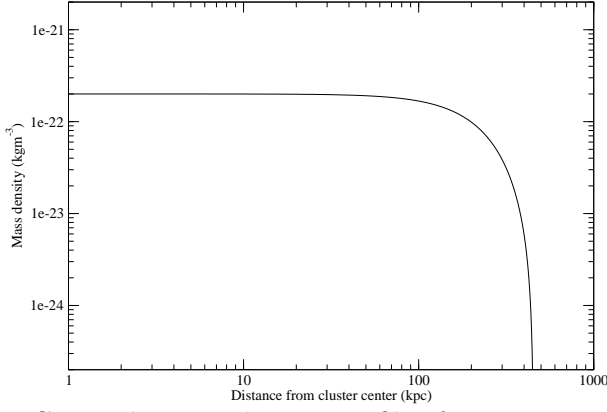


FIG. 1. The mass density profile of a neutrino star with central mass density $\rho_\nu = 10^{-25} \text{ gcm}^{-3}$ with a neutrino mass of 3 eV

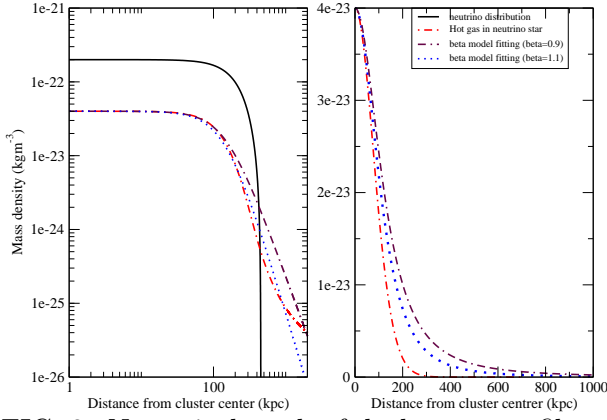


FIG. 2. Numerical result of the hot gas profile and beta model fitting with $T=10^8 \text{ K}$, $r_c=150 \text{ kpc}$ and $n_g=20000$ at the center. Right panel: hot gas profile together with beta model fitting. Left panel: the central core of the hot gas in log scale: dark matter profile is also shown (solid line).

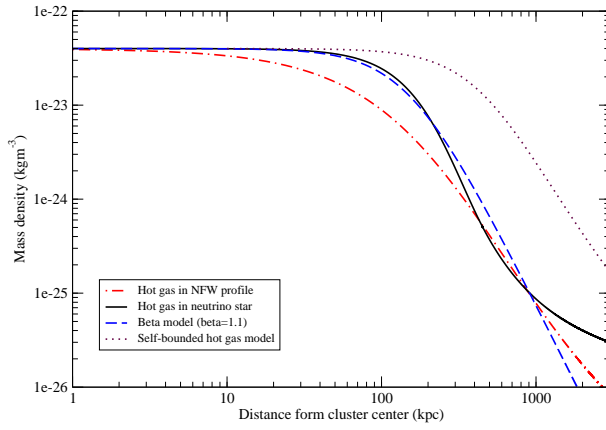


FIG. 3. Hot gas profiles in four different models: NFW model from CDM simulation, with $r_s=300$ kpc (dot-dashed line), neutrino star model (solid line), beta model (dashed line), and self-bounded model (dotted line). For the latter three models, same parameters as in Fig. 2 have been used

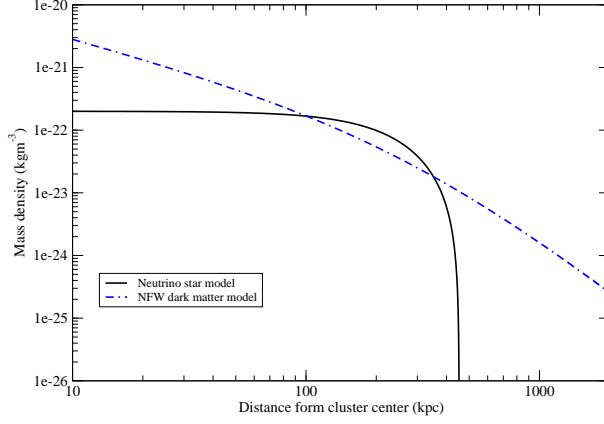


FIG. 4. Dark matter profiles in neutrino star model (solid line) vs. NFW model from CDM simulation, with $r_s=300$ kpc (dot-dashed line). Same parameters as in Fig. 2 have been used.